14499

Wax

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ANTENNAS, REFLECTORS AND NET PATH LOSS CONSIDERATIONS AND THEIR EFFECT ON CHOICE OF OPERATING FREQUENCY, TRANSMIT POWER AND DATA RATE FOR PACKET RADIO SYSTEMS

1.0 INTRODUCTION

In the Packet Radio Network being investigated, it is desired that a system model be derived that provides a maximum of traffic flow both within a given area, and out of a given area through gateway station(s). The relation between traffic flow within a defined area and flow out of the area (i.e. local vs. long distance traffic) has not been defined but may not be too significant to specification of a system model if the area is large relative to the spacing between repeaters as is likely to be the case. For such a model, it is the optimization of the flow of traffic across a given area that is of importance.

Most previous investigations have been concerned with defining models in the time domain to achieve the desired goal. However, it becomes obvious immediately that both frequency and space (i.e. separation) are factors affecting our system model because interference between various elements of the system has a strong impact on our effective use of time. We therefore have at least three fundamental parameters affecting optimization of traffic flow. These are time, frequency, and space. This note is indirectly concerned with the space aspect of the problem since it is directed primarily to the directivity characteristics of antennas. However, results can have a strong influence on the choice of frequency band. For example, it is shown that in comparing the ratio of net space loss between pairs of isotropic antennas and between pairs of antennas with a constant aperture, this ratio changes inversely as the fourth power of frequency. This quickly leads one to the conclusion that if omni antennas are to be employed, we should choose the lowest available frequency consistant

with reasonable size omni antenna. Such an approach is further supported by the fact that transmitter efficiencies and maximum available output power tends to be highest at the lower frequencies.

The same relation indicates that if directional antennas are employed we should choose the highest available frequency consistant with reasonable losses from rain attenuation. The efficiency and power output characteristics of solid state devices is a somewhat negative factor here, but is not near as significant as the gain achieved from moderate size antenna apertures. Further the efficiency of microwave sources is steadily improving with development of higher frequency transistors.

Though the 4th power relationship can have a very strong impact on equipment design, it is the potential for very large increases in traffic flow resulting from both "space division" and increases in coherency bandwidth that make use of directive antennas, coupled to low cost, low powered transmitters, most attractive. More detail on this subject is reserved for a future note.

The following is concerned primarily with the concept of an antenna as an aperture. The space loss equation is derived to emphasize the fact that the frequency dependent term is the result of our antenna model (isotropic) chosen in defining space loss. Examples of transmit powers required for 100 KB/S data over 5 mile line of sight paths are calculated for several reasonable antenna configurations and frequencies, and it will be noted that required power varied over a range of about $4X10^7$ for the chosen examples. Examples are also given for transmission paths that include flat reflectors since they will exist with omni antennas in an urban environment by accident if not by design.

Examples are given for antennas which are omni directional in the azimuth plane and antennas which have high directivity in both planes.

this subject has not been covered in much detail, and it is believed that an exhaustive treatment is not needed for the system decisions to be made. If omni antennas are chosen the gain characteristics will vary from what we can achieve with vertical dipole, to that that can be achieved with a biconical, the dimensions of which will be determined by how much we wish to shape the vertical pattern.

If we choose to use antennas with high directivity in both vertical and horizontal planes, any configuration we might choose, even if it approaches an aperture efficiency of 100% will not have characteristics sufficiently different from horns or paraboloids to significantly affect our system model. Phased arrays have been intentionally avoided and this subject will be reviewed in future notes. However, even here the concept of antenna aperture is valid and it is only the ability to rapidly change the phase of the various elements within the aperture that gives the phased array special characteristics.

The subject of rain attenuation is also briefly addressed and it will be noted that this does not become a significant factor in the selection of operating frequency at frequencies below about 10 GHZ. The subject of multipath fading over line of sight paths with directivve antennas is only addressed with respect to coherency bandwidth since it is believed the Packet Radio System will employ relatively short paths (i.e. less than 10 miles) even if directive relays are used. There is adequate data to support the opinion that little margin for fading is needed for such short paths unless they are very reflective (i.e. our water).

The subject of coherency of line-of-sight paths is very briefly discussed in Section 7 and two references are given. There is considerable evidence to support the statements relative to the large coherency bandwidths of most line-of-sight paths when directive antennas are employed. Both this subject and the multipath question will be addressed further in future notes if "space division" by means of directive antennas is to be considered as a means of increasing system effectiveness.

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FREQUENCY BANDS

Possible operating frequencies for the ARPA Packet Data Network are listed below with the corresponding midband wavelength, area of an isotropic antenna and gain of an effective 1 sq. ft. aperture. The lowest frequency listed is 406 MHz though a lower frequency is desirable for the hand held terminal if they may be operated at low data rate. At least some of these bands are further divided, hence they may not be available for communication type services. Also Government band around 10 GHZ (X band) has been omitted since it is likely well occupied by radar systems, hence it is an unlikely choice for a test system. (The same might also apply to part of L band listed) The primary purpose of the listing is to provide reasonable examples of possible frequencies over more than a decade frequency range. Government bands were chosen but even the industrial, public safety or common carrier bands are likely candidates for at least a test system operating under an experimental license.

The purpose of including the area of an isotropic antenna and gain of an effective 1 sq. ft. aperture will be obvious when reviewing the characteristics of typical antennas listed under Section 4.

Possible operating frequencies for the ARPA Packet Data Network are listed below with the corresponding midband wavelength, area of an isotropic antenna and gain of an effective 1 sq. ft. aperture.

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TABLE 1
FREQUENCY BANDS

FREQ IN MHZ	WAVELENGTH* λ (FT)	WAVELENGTH* λ (INCHES)	AREA OF ISOTROPIC ANTENNA SQ.FT.	GAIN IN DB ABOVE ISOTROPIC OF 1 SQ. FT EFFECTIVE APERTURE
406-420	2.4	28.6	0.46	3.36 db
1700-1850	0.55	6.1	2.4×10^{-2}	16.2
2200-2300	0.44	5.2	1.54×10^{-2}	18.1
4400-5000	0.21	2.5	3.34×10^{-3}	24.75
7125-8500	0.125	1.5	1.24×10^{-3}	29.06
13200-16000	0.067	0.8	3.88×10^{-4}	34.1

* ALL WAVELENGTHS, AREAS AND GAIN ARE FOR MIDBAND FREQUENCY OF BAND LISTED

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2200-2300	0.44	5.2	$1.5X10^{-2}$	18.1
4400-5000	0.21	2.5	$3.3X10^{-3}$	24.75
7125-8500	0.125	1.5	$1.2X10^{-3}$	29.05
12200-15000	0.067	0.8	$3.8X10^{-4}$	34.1

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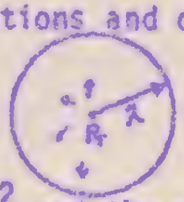
3.0 ISOTROPIC ANTENNAS AND SPACE LOSS

This section contains a very basic discussion of the concept an isotropic antenna and a derivation of the space loss equation. The primary purpose of this brief summary of a very fundamental concept is to emphasize that the space loss equation is derived from the field intensity and capture area concepts of isotropic antennas which may not be the desired model for point to point systems. For example; for the frequencies being considered it might be just as reasonable to derive the space loss equation in terms of the loss between two antenna apertures of a fixed area since cost is more related to antenna area than frequency as antenna surface tolerance does not present a major cost problem over the frequency range being considered.

3.1 THE ISOTROPIC TRANSMITTING ANTENNA

Consider a lossless point source of RF radiation which radiates the transmitter power P_T equally in all directions and consider a sphere of radius of one wavelength λ.



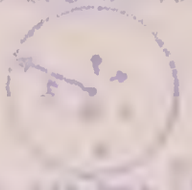
The area of this sphere is the $4\pi\lambda^2$ and the power density P_D on the surface of this sphere is $P_D = \frac{P_T}{4\pi\lambda^2}$

Likewise the power density at any distance d is $P_D\big|_d = \frac{P_T}{4\pi d^2}$.

Note that the field is spherical though at any distance and for any receive antenna apertures of interest we may consider the field a plane wave over the receive antenna aperture.

3.2 THE ISOTROPIC RECEIVE ANTENNA

A point source of radiation is a convenient concept for a transmitting antenna but the purpose of a receive antenna is to extract energy from the field and it is a little difficult to visualize a capture area for a point. However the hypothetical isotropic receive antenna does have a capture area defined as $A_i = \frac{\lambda^2}{4\pi}$



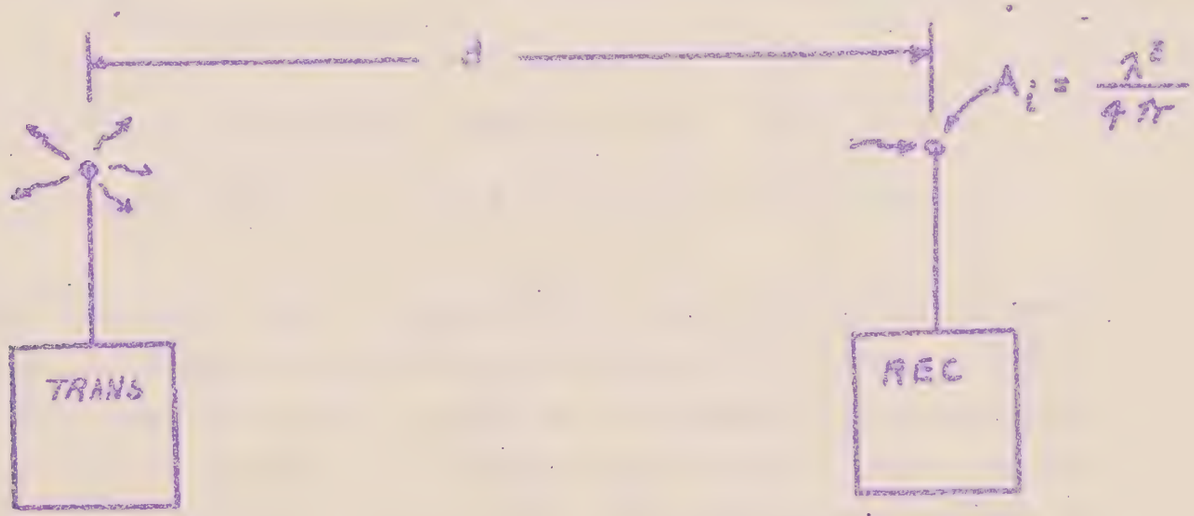
NOTE: This probably can be derived from some very fundamental field theory relationships. Kraus[1] takes a somewhat devious route to this proof. He first proves a proportionality relationship between antenna capture area and directivity and then derives the capture area and directivity for a realizable antenna (i.e. short dipole). He then calculates the effective area of the isotropic antenna by relating the directivity of the isotropic antenna (unity by definition) to the directivity and capture area of the dipole antenna.

The concept of effective antenna aperture is a convenient one in working with practical microwave antennas such as paraboloids and horns since a physical relationship exist between the effective aperture and the antenna surface. For other antennas such as a small dipole the idea of capture area is of less concepted value.

The important point to note is that our reference isotropic receiver antenna has a capture area that is a function of the square of wavelength or inverse square of frequency..

3.3 SPACE LOSS EQUATION

From the power density and capture area concepts summarized above derivation of the space loss equation is straightforward.



Space loss is defined as the power ratio between that transmitted and that received by lossless isotropic transmit and receive antennas.

At distance d the power density at the receiver due to transmitter power P_T is:

$$P_D\Big|_R = \frac{P_T}{4\pi d^2}$$

and receive power is:

$$P_R = A_e P_D = \frac{\lambda^2}{4\pi} \cdot \frac{P_T}{4\pi d^2} = \frac{\lambda^2 P_T}{(4\pi d)^2}$$

and space loss α

$$\alpha = \frac{P_T}{P_r} = \frac{P_T}{\frac{\lambda^2 P_T}{(4\pi)^2 d^2}} = \frac{(4\pi)^2 d^2}{\lambda^2}$$

since $\lambda = \frac{c}{f}$ (where c = velocity of light)

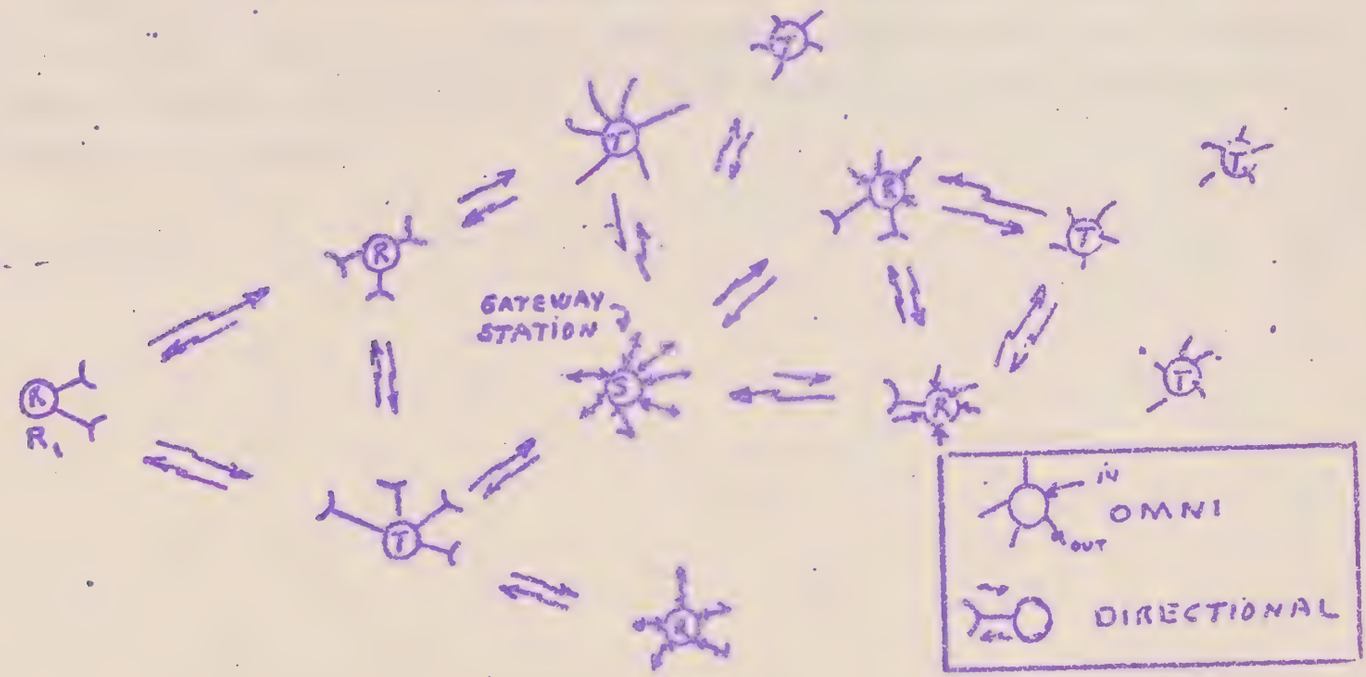
$$= \frac{(4\pi)^2 \; d^2 \; f^2}{c^2}$$

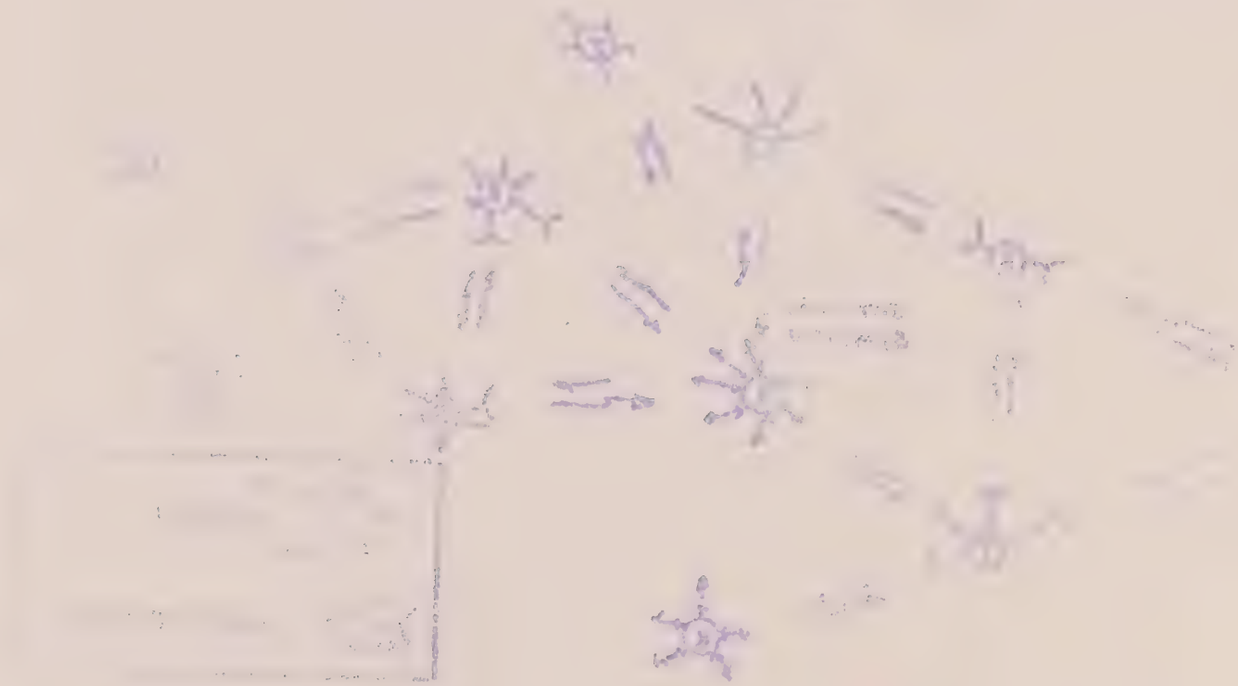
For d in miles and f in MHZ this reduces to $\alpha = 4580 \; f^2 \; d^2$ or in db the familiar formula $\alpha = 36.6 + 20 \log f + 20 \log d$.

It is seen that space loss increases as the square of distance between transmitter and receiver as would be expected due to spreading of the signal. The space loss also increases as the square of frequency and this is the direct result of our choice of an isotropic antenna as our reference receiving antenna, and its effective area decreases with increasing frequency. If we had chosen a constant effective aperture independent of frequency as our receive antenna, then our space loss

equation would be independent of frequency. Of course we would have to tolerate the increase in directivity with increasing frequency that results from such a configuration.

If we chose constant apertures independent of frequency for both transmit and receive antennas then the directivity of both antennas increases with increasing frequency, and again the 20 log f term appears in the space loss equation but with a change in sign. That is for this configuration space loss decreases with increasing frequency. The point of emphasizing the above is that all three configurations mentioned may have application in the ARPA network and could have a strong impact on the choice of frequencies. That is,we may wish to communicate between stations with omni antennas and repeaters or terminals with directive antennas and we may wish to communicate between repeaters and terminals both using directive antennas, i.e.





The incentive for considering directive antennas is both increased system capacity and reduced transmit power. For example, if repeater R_1 is located on the border of an area to be covered, we can choose the aperture to cover the desired area and not only save in the transmit power needed but also reduce the mutual interference between this repeater and other systems.

The power gain may be a very significant factor affecting equipment design, choice of frequency and cost. For example, a 6 ft. paraboloid antenna has a gain of about 40 db in the 7625 to 8520 MHZ Government band. Therefore if we use 6 ft. antennas for both transmit and receive we get a reduction of 80 db in net path loss over omni antennas and therefore can get with a 10 milliwatt transmitter the same performance as a 1 megawatt transmitter using omni antennas. In fact in most environments the 10 mw transmitter with directional antennas would work better since performance will not be limited by multipath from reflections at large azimuth angles off beam. This makes it practical to consider use of a moderate number of low power, high data capacity relays in a directive network designed with sufficient alternate routing to insure communication through the network.

4.0 Gains of Typical Antennas

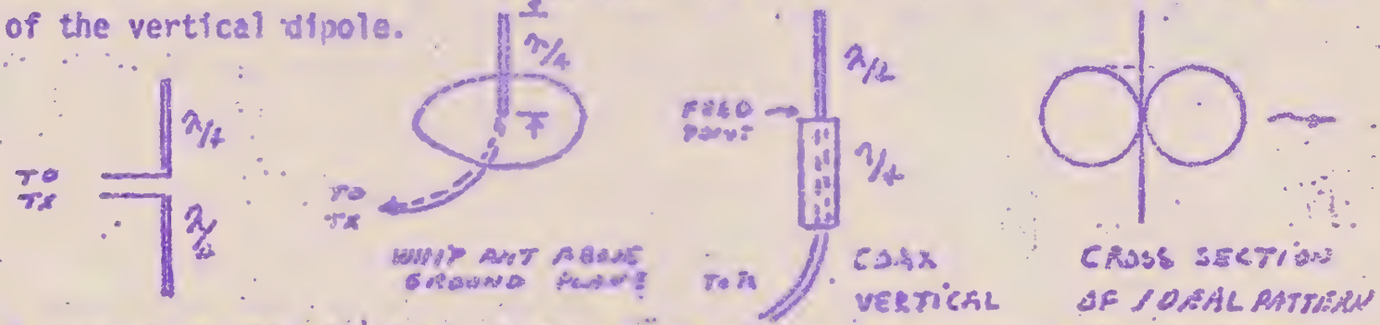
The purpose of this section is to provide examples of typical antennas that may be used for Packet Radio System operating at frequencies abcve 400 GHZ.

4.1 Omni Antennas

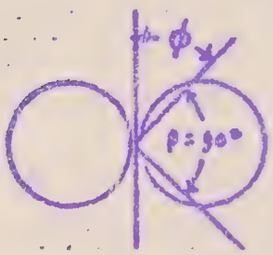
Omni directional antenna is used here to mean an antenna which radiates equally to all points in azimuth only. Antenna may have vertical directivity as long as the veritcal directivity is not so great as to require excessive care in positioning. Since most practical antenna structures for Packet Radio Systems will be size limited, excessive vertical directivity is not likely to become a problem even at frequencies in the microwave region.

4.1.1 Vertical Dipole

Many simple antennas used for applications such as mobile radio are versions of the vertical dipole.



A very short thin dipole (relative to λ/4) has a normalized directivity pattern equal to sine β where β is angle from antenna axis.



The directivity of this pattern is $4/\pi$ or about 1 db (pattern is doughnut shaped with cross section as shown)

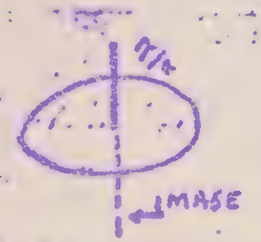
If the dipole antenna is formed from two 1/4 λ elements the normalized pattern is $\frac{\cos\left(\frac{\pi}{2}\cos\phi\right)}{\sin\phi}$ which is only slightly more directional than the short dipole.

Half power beam width is 73° instead of 90°. Gain is about 0.4 db greater than that of the small dipole.

The capture area of a 1/2 λ dipole and the very short dipole are also about the same. (i.e. 1.64 $\lambda^2/4\pi$ vs. 1.5 $\lambda^2/4\pi$)

NOTE: This might lead one to question why not use very small dipoles. However as the antenna length is decreased the radiation resistance decreases and the reactive component increases, hence I^2R losses increase resulting in poorer efficiency.

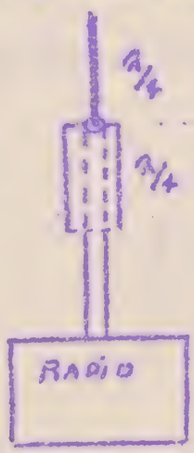
The common 1/4 λ vertical antenna above a ground plane is a form of the dipole since the image element is formed in the ground plane.



It is quite important that the ground plane have good conductivity since it is the current in the ground plane that forms the image. For example, a 1/4 λ vertical broadcast antenna operating into a poor ground system can easily dissipate 3/4 the transmitter power in resistance losses in the ground within a radius of 1/2λ from the antenna.

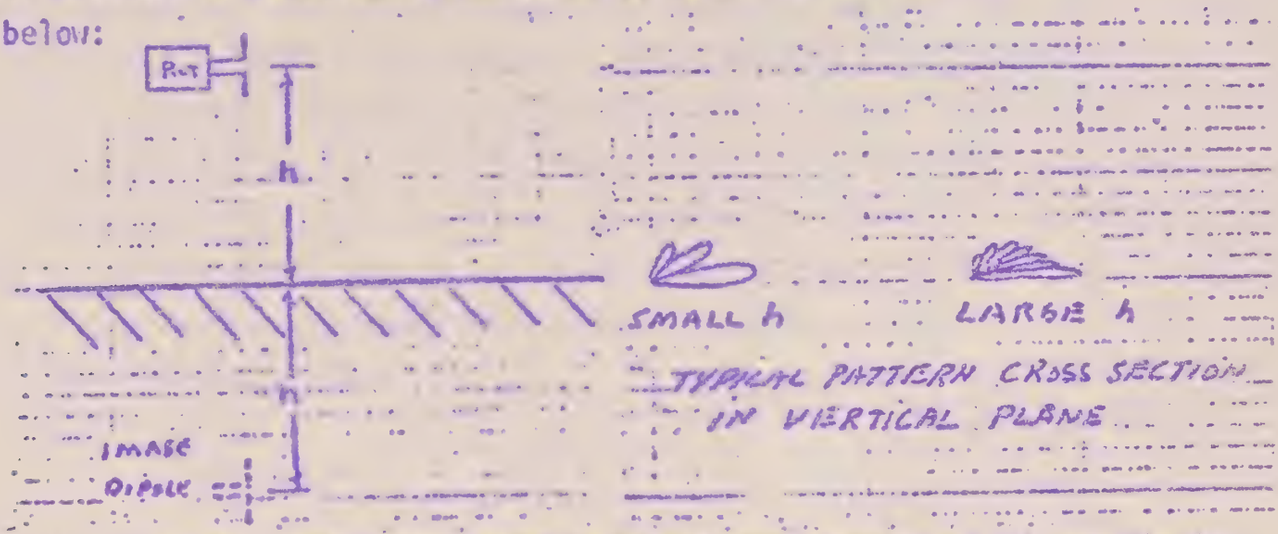
A common antenna for hand held radio systems (i.e. 27 MHZ Citizensband) is a whip approaching 1/4 λ . It is a little difficult to define whether such an antenna is a form of a center fed dipole with the users body as one dipole element, capacity coupled through the radio, or as a ground plane. It is probably more closely akin to the ground plane since the users feet can't very well be a high impedance point on the antenna (unless the user is a parachute jumper). In any event such antennas tend to be inefficient.

For the frequencies of interest for Packet Radio antennas need not be particularly inefficient since even in the 406-420 MHZ band the size is small (i.e. $\lambda/4 \approx$ 6.5 inches) and even a ground plane is a practical dimension in a hand held terminal though a coax vertical would likely be more convenient because of its shape.



Earth Reflections on Vertical Pattern

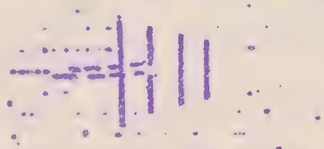
The patterns for the simple antennas discussed above are free space patterns. In most practical environments patterns are drastically modified by the environment. Even over smooth conducting earth the vertical pattern is drastically modified by ground reflection as shown below:



For smooth earth the reflection makes a two element array out of our single element antenna and since h may in some instances be many wavelengths, the pattern may contain many lobes.

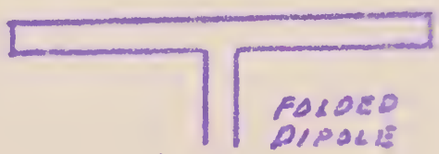
4.1.3 Simple Horizontally Polarized Antennas

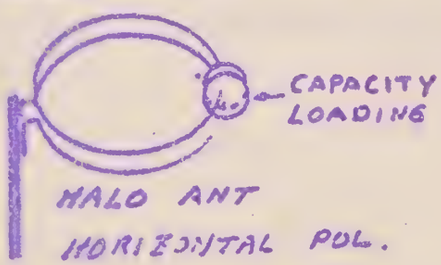
In the above it was assumed that the antenna would be oriented with the plane vertical since there is a null off the ends of the antenna. However, in some cases use of the horizontally directive arrays may be desirable to cover a specific area and to provide protection from interference outside the desired area. For fixed stations the yagi antenna with parasitic elements makes a simple antenna i.e.



An antenna with essentially omni characteristics that may be used in a portable or mobile unit talking to the horizontally polarized directional repeater or station, is the Halo antenna.

This antenna is essentially a folded dipole arranged in a circle and end loaded.

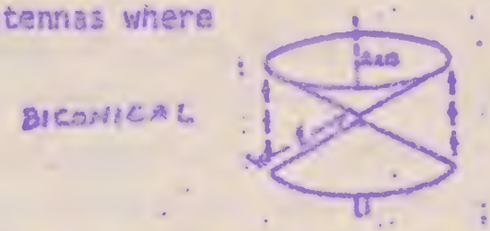




This antenna has been used at about 50 MHZ for mobile applications where a horizontal dipole antenna would be excessively large.

4.1.3 Omni Antennas with Moderate to High Directivity

Antennas discussed above all have some directivity but have been oriented to be omni directional in the azimuth plane. However, the vertical directivity of the antennas discussed is also small. Vertical directivity can be increased with resulting increased gain in the azimuth plane. This can be accomplished with vertically stacked arrays as for example as are used in FM and TV broadcast bands. For the microwave region waveguide fed slot arrays are essentially the equivalent of the stacked arrays used at lower frequencies. Also in the microwave region moderate gain can be achieved with biconical type antennas where



dimension l is long compared to a wavelength. Such antennas can be considered as a degenerate horn in which the mouth of the horn in the horizontal plane is opened to 360 degrees. Such antennas also have wide bandwidth and this factor has contributed to their use in some applications. Gains of 8 to 12 db are available from reasonable size structures in frequency bands of 6 to 12 GHZ.

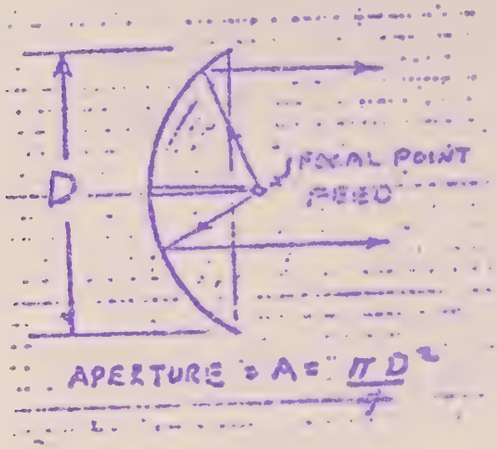
4.2 Antennas With High Directivity

It is in the consideration of antennas with high directivity that the concept of an antenna as an aperture becomes convenient. Where the antenna area is large compared to λ the gain over isotropic may be quite large. Further we can design quite nonsymetrical structures so as to achieve narrow beamwidth in one plane and wide in the other. For example, we may wish to cover a 45° pattern in azimuth but wish maximum vertical directivity to allow operation with minimum transmit power.

4.2.1 Paraboloids and Horns

Two very common directive antennas are the paraboloid and pyramidal horn. Characteristics of interest are summarized below:

a. Paraboloid Antenna



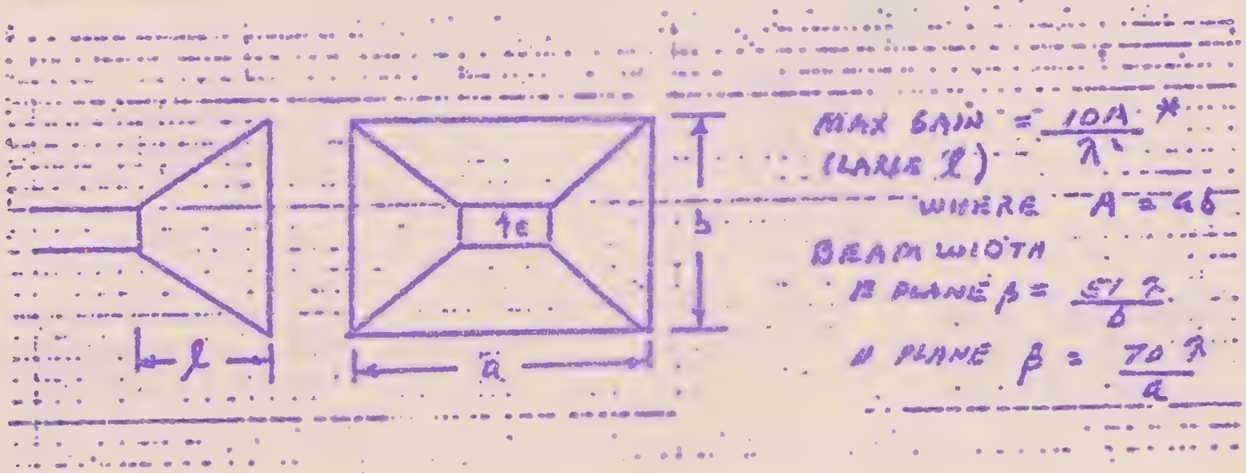
Gain above isotropic $\simeq \frac{7A}{\lambda^2}$

Effective Area = $A_e \simeq 0.55A$

Beamwidth $= \beta \simeq \frac{70}{D}$

NOTE:
Gain and beamwidth relations given for a paraboloid assumes 10 db taper of energy from center to edge of dish which is typical for a focal point fed paraboloid. The aperture efficiency of such an antenna is about 0.5 to 0.6. This taper is constrained by feed design limitations. In large aperture antennas, employing cassegrain configuration, efficiencies approaching 80% have been achieved. In such a system the subreflector is shaped to obtain the desired illumination taper and the antenna surface is then shaped to correct for the phase error introduced by subreflector shaping.

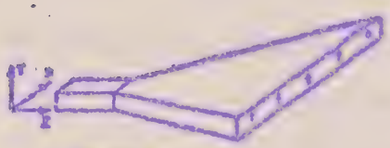
b. Horn Antenna



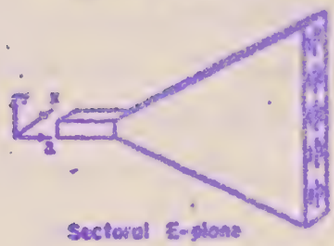
NOTE:
Gain for horns shown is for optimum relation of a, b, and ℓ. Practical horns may vary considerably from above values. A value relation of: Gain = $6A/\lambda^2$ is closer to that achieved in practice with more desirable dimensions.

4.2.2 Directional Antennas With Very Non-Symetrical Patterns

There are many possible configurations of antennas which produce very non-symetical patterns. Some of the more common are shown in sketches below.



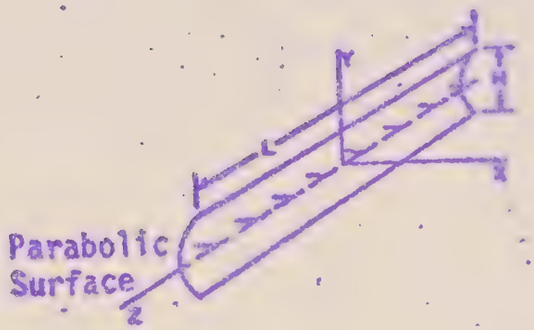
Sectoral H-plane



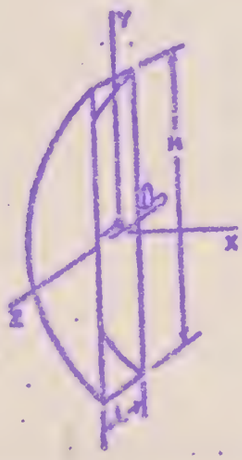
Sectoral E-plane

TEM biconical

TE_{01} biconical



Linear Array, High Directivity in the X-Z Plane.

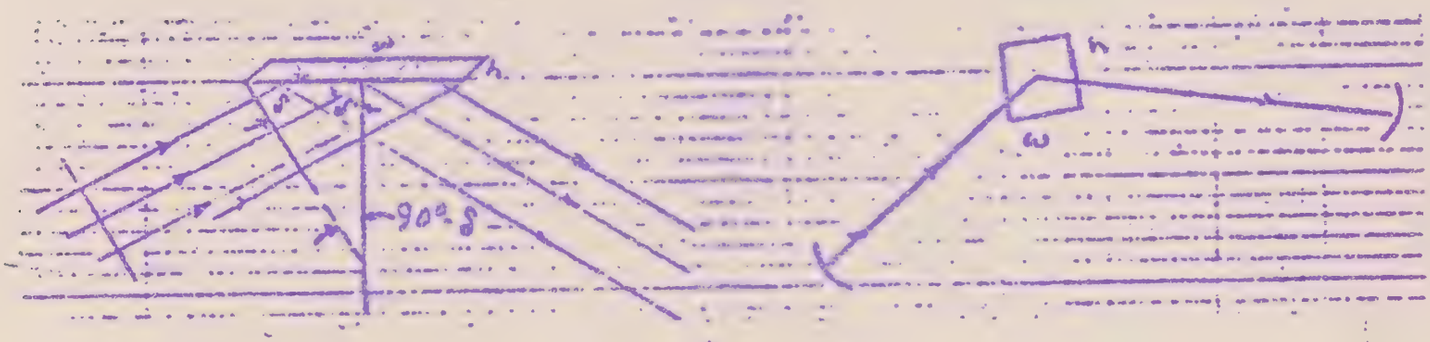


"P111 Box" Antenna High Directivity in the X-Y Plane.

Antennas such as those sketched above can be designed for almost any desired coverage pattern. However, the side lobe characteristics can become a significant factor controlling the design if the objective of the design as to protect from interference off beam. (This subject will be discussed further in a future note being prepared by R. L. Kaiser)

4.2.3 Directional Characteristics of a Flat Conductive Surface

Flat surfaces with dimensions much larger than one wavelength are sometimes used to redirect a microwave path over an obstruction. The ARPA Packet Radio Transmission System is not likely to intentionally employ such reflectors, but they will be in some paths in the form of metal buildings, etc. Therefore, it is of interest to define the gain of a flat reflector located in the far field with constant illumination over the surface of the reflector.



The effective area of the reflector is the projected area normal to the direction of the incident wave. In the case where the transmit antenna, reflector and receive antenna are in the same plane, the effective area of a flat reflector is: $A_e = (wh)\cos\delta$ where δ is the angle of the incidence ray from the normal to the reflector.

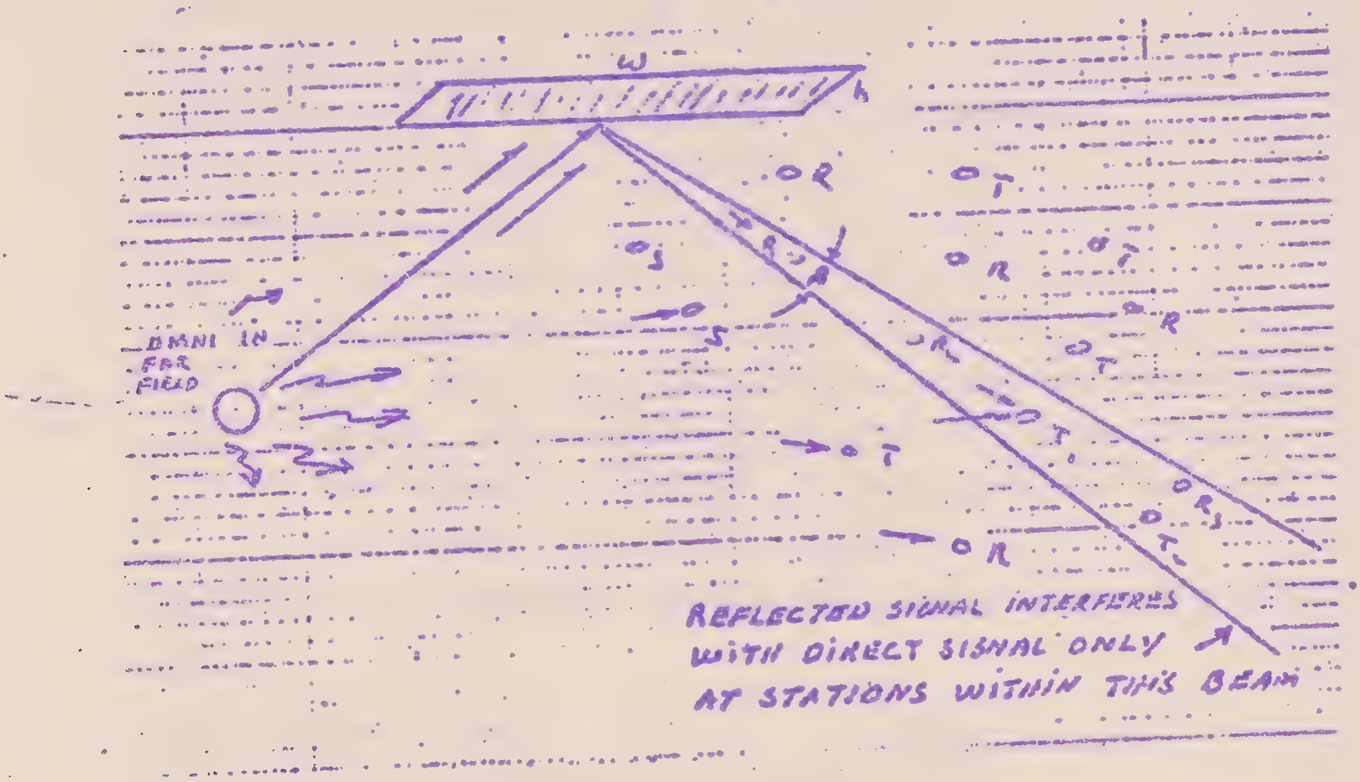
The gain over isotropic is: $G_R = \frac{A_e}{A_i} = \frac{A_e}{\frac{\lambda^2}{4\pi}} = \frac{4\pi A_e}{\lambda^2}$

And 1/2 power beamwidth is: $\beta \simeq \frac{58.7\,\lambda}{L}$

where: L = the effective lineal dimension of the passive reflector in the plane in which β is measured.

It is noted from above that for reasonable size structures that the gain of a flat reflector may be quite large. For example, a reflector 16' high by 32' wide at 8 GHZ and angle δ = 20° will have a gain of about 56 db and a beamwidth in the azimuth plane of about .025 degrees.

The beamwidth may be quite small. For example, we may illuminate the flat surface of a building from an omni antenna but if the surface is flat the effect of the echo is seen only in a limited path i.e.



The fact that reflector gain may be very large should not be of concern since gain is defined with respect to a reflector of area $\lambda^2/4\pi$ which is quite small for signals in the microwave region. We never get more echo signal at receive position than the direct signal if the direct signal is unobstructed. This will be made clearer from the numerical examples given in section 5 below.

5.0 Examples

A few examples are given below to illustrate the power advantages of using directional antennas. The following standard conditions are taken for all examples.

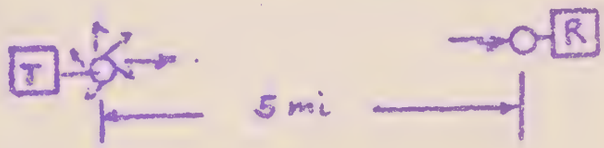
a. Receiver noise figure = 6 db
b. Data Rate = 10^5 B/S
c. Bandwidth = $2X10^5$ (i.e. adequate for Bi-Phase Mod)
d. Noise Level = -174+53+6 = -115 DBM
e. Required S/N = 20 db

NOTE: (Without interference bi-phase PSK will provide adequate error rate with 10 to 13 db S/N. The margin assumed here is to get the signal well above thermal noise so that interference will control error rate. This also provides a slight margin, but not near enough, for fading on long paths)

f. From d & e above required receive power = P_R = -115 + 20 = -95 DBM

5.1 Example 1

Frequency = 406-420 MHZ
Receiver and transmit antennas = isotropic
Path Length = 5 miles



Space Loss = α = 36.6 + 52.2 + 14 $\simeq$ 103 db
Therefore:
Transmit Power = $P_T = \alpha + P_R$ = 103 - 95 = **+8 DBm**

5.2 Example 2, 400 MHZ using 4' parabolcid antennas

Frequency = 406-420 MHZ

Receive and Transmit Antenna = 4' Dia. (Gain = 11.7 db)

$$P_T = \alpha - 2(G_A) + P_R$$

Required Transmit Power = 103-2(11.7) -95 = **-15.4 DBM**

5.3 Example 3, 8 GHZ Band, Isotropic Antenna

Antenna = Isotropic

Space Loss = 36.6 + 78 + 14 = 128.6 DB

P_T = 128.6 - 95 = **+33.6 DBM** (2.3 watts)

5.4 Example 4, 8 GHZ, 4 ft. Antennas

$P_T = \alpha - 2G_A + P_R$

P_T = 128.6 - 2(37.4) -55 = **-42.2 DBM** Less than 1/10 microwatt

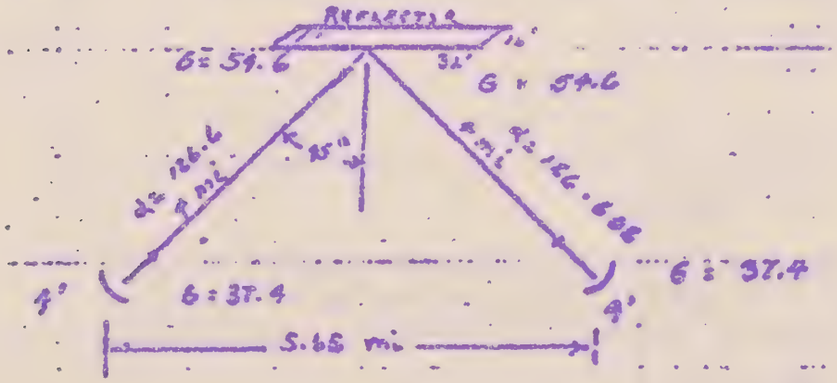
5.5 Example 5 Moderate Size Horn at 8 GHZ With Aperture Efficiency of 0.45

Horn Aperture = 1.3 Sq. Ft. (i.e. approximately 12X16" aperture)

$$\text{Gain} = \frac{A_e}{A_i} = 10 \log \frac{1.3 \times 0.45}{1.24 \times 10^{-3}} = 26.2 \text{ DB}$$

P_T = 128.6 - 2 (26.2) -95 = -18.8 DBM

5.6 Example 6, 8 GHZ System With Passive Reflector



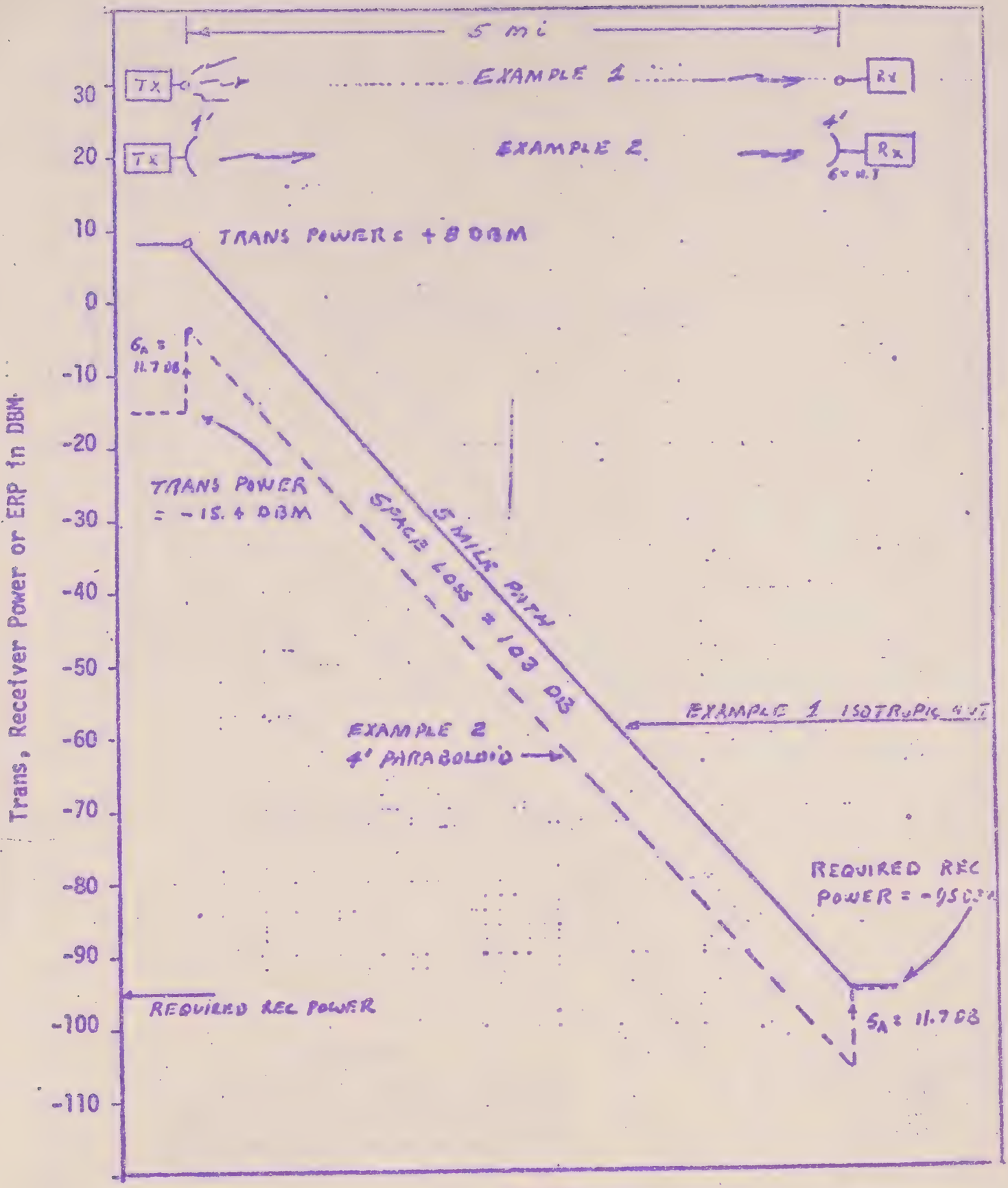


FIGURE 5-1

Graphical Power, Antenna Gain and Space Loss Relationship for Omni and Directive Antennas. Examples 1 & 2. Frequency Band 406-420 MHZ. Antennas Omni and 4' Paraboloids.

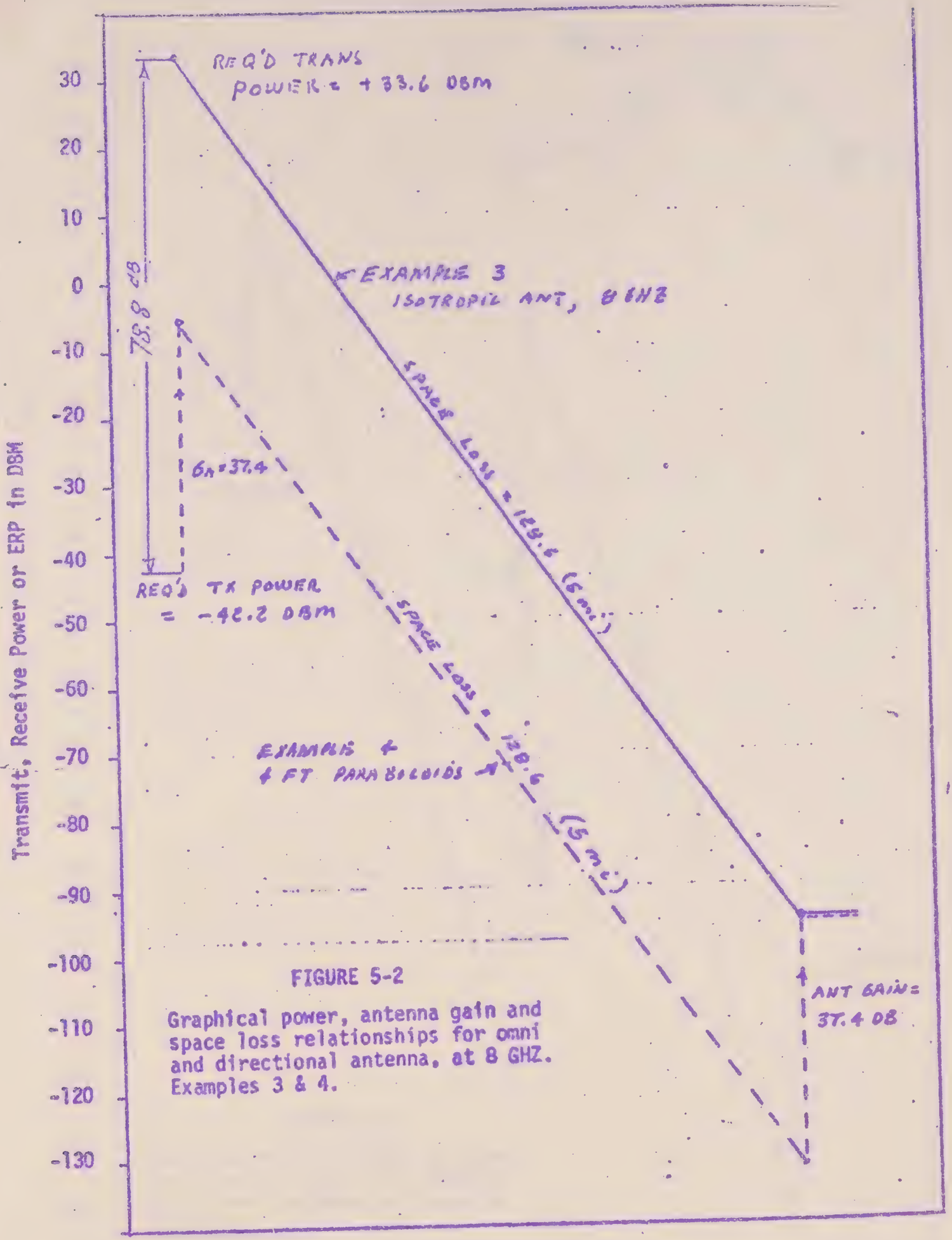


FIGURE 5-2

Graphical power, antenna gain and space loss relationships for omni and directional antenna, at 8 GHZ. Examples 3 & 4.

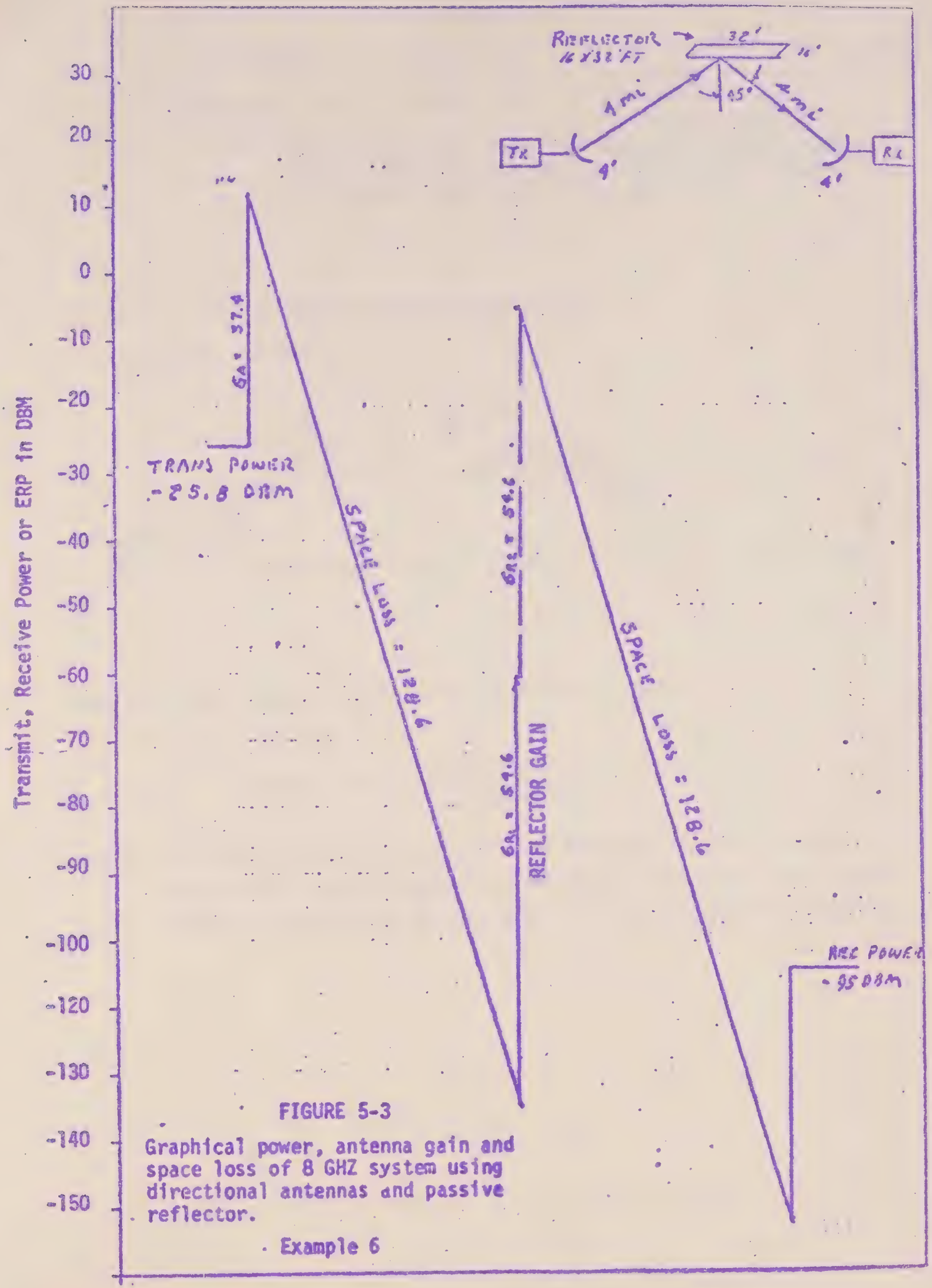


FIGURE 5-3

Graphical power, antenna gain and space loss of 8 GHZ system using directional antennas and passive reflector.

Example 6

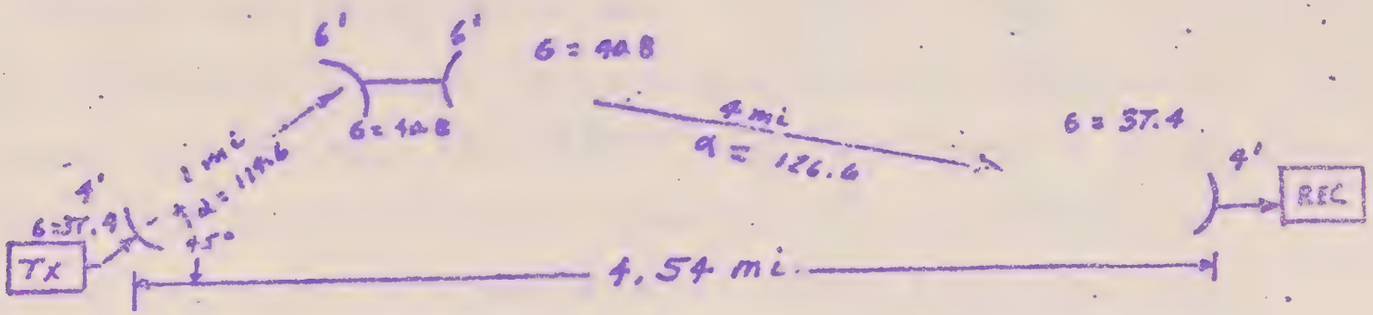
Net Path Loss = -37.4 + 126.6 - 54.6 - 54.6 + 126.6 - 37.4 = 69.2 db

Transpower = P_T = 69.2 - 95 = **- 25.8 dbm**

NOTE: For direct path with 4 ft. antennas the net path loss = 54.8 db hence the passive repeater resulted in an additional loss of 14.4 db.

5.7 Example of Passive Repeater Using Paraboloids

Frequency = 8 GHZ



Net Path Loss = -37.4 + 114.6 - 2(40.8) + 126.6 - 37.4

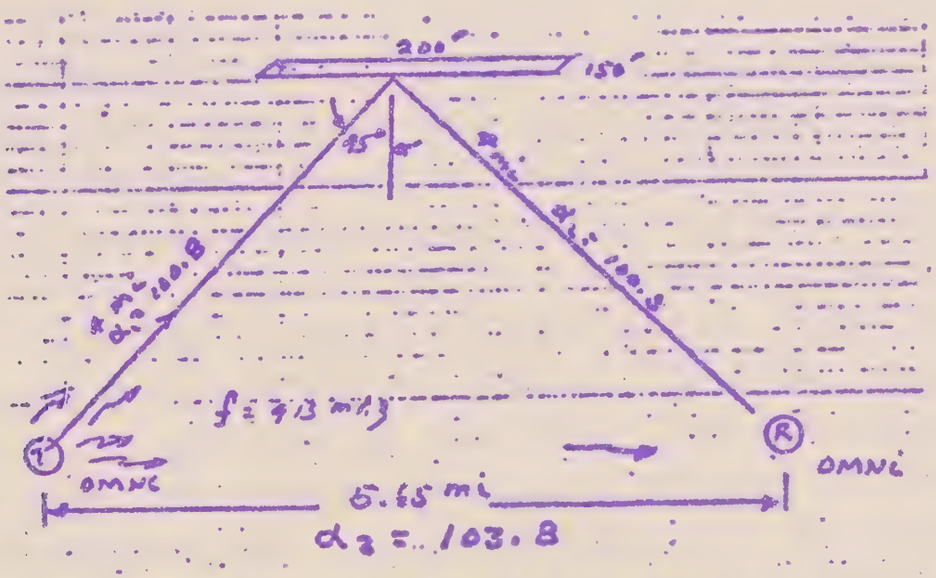
= 85.8 db

P_T = 85.8 - 95 = **-9.2 dbm**

NOTE: If CLEAR DIRECT PATH were available Net loss = -2(37.4) + 127.7 = 52.0 db and required transmit power would be 52.9 -95 = -42.1 dbm or about 1/2000 or 33 db less than for case with passive repeater.

5.8 Example 8 Echo at 400 MHZ

Example 6 above indicates that substantial echo can occur. The gain of the reflector is a function of both size and surface tolerance. Where surface tolerance is poor this has the effect of reducing the effective area and broadening the beam. In urban areas quite large surfaces can have sufficient reflectivity and surface tolerance to be efficient reflectors. Even relatively low loss materials such as glass and water may have relatively high dielectric constant (and hence index of refraction) and therefore can be efficient reflectors. For example, glasses have dielectric contents that range from about 3 to 8 and hence refractive indices in the microwave region that range from about 1.7 to 4. Metalized glass is becoming a popular surface material for large commercial buildings and because of the smooth surface are likely good reflectors even at frequencies above 12 GHZ. It appears reasonable that one might easily encounter a reflector with an effective area at 400 MHZ of 200X150 = 30,000 sq. ft. and this is used for the example below.



Reflector Gain = $\frac{A_e}{A_i} = \frac{(150 \times 200)\cos 45°}{0.46} = 46,000 = 46.6$ dB

Net Path Loss Over Reflecting Path = $2(100.8) - (46.6) = 108.4$ dB

Net loss over direct path is = 103.8

Therefore, for this example the echo is only 4.6 db below the direct signal and the delay is about 11.5 microseconds. If the direct ray experienced some obstruction loss the reflected signal could easily be larger than the direct ray.

NOTE: The far field criteria commonly used for the gain of large symetrical surfaces is $2D^2/\lambda$. The distance in the above example is just within this criteria. (D = Diameter of surface)

5.9 Example 9

The purpose of this example is to illustrate that we need not use a separate transmitter for each direction in a multidirection network if we wish to time share the transmission and use a high data rate (i.e. 1 to 10 MB/S.) This technique is most effective for one direction (i.e. broadcast)* systems but need not be restricted to this if separate receivers are added to each path. With some care in planning system layout all incoming signals may also be on a common receive frequency each carrying different information. This obviously would be most practical for one central gateway station in an area "talking" to a number of distributed repeaters.

5.9.1 System Model

It is desired that a central station radiate to a number of remote repeaters that vary considerably in distance. Four stations are located within a radius of 3 miles and two other stations are located at radii of 5 and 10 miles. We should provide some fade margin for the 10 mile path and it is assumed that it has been determined that 20 db is adequate. (Even for Rayleigh fading, which isn't likely to exist much of the time on a 10 mile path, this margin gives a reliability of 99.3%). It is also assumed that we do not wish to use an antenna larger than 4' and for smaller apertures, horns will be used. The frequency of operation is about 8 GHZ. For this model it is obvious that the long path controls, due to the assumed 20 db fade margin. Less fade margin is adequate for shorter paths. Therefore 1/2 the total transmit power will be used for this path and the remainder divided among the other paths. Therefore as a test example consider the configuration below where all remote stations use horn antennas.

* Technique shown is commonly used for CATV and ETV networks.

Therefore, for this example the echo is only [illegible]
and is delay is about 11.5 microseconds. [illegible]
the obstruction does the reflected signal [illegible]

[illegible]

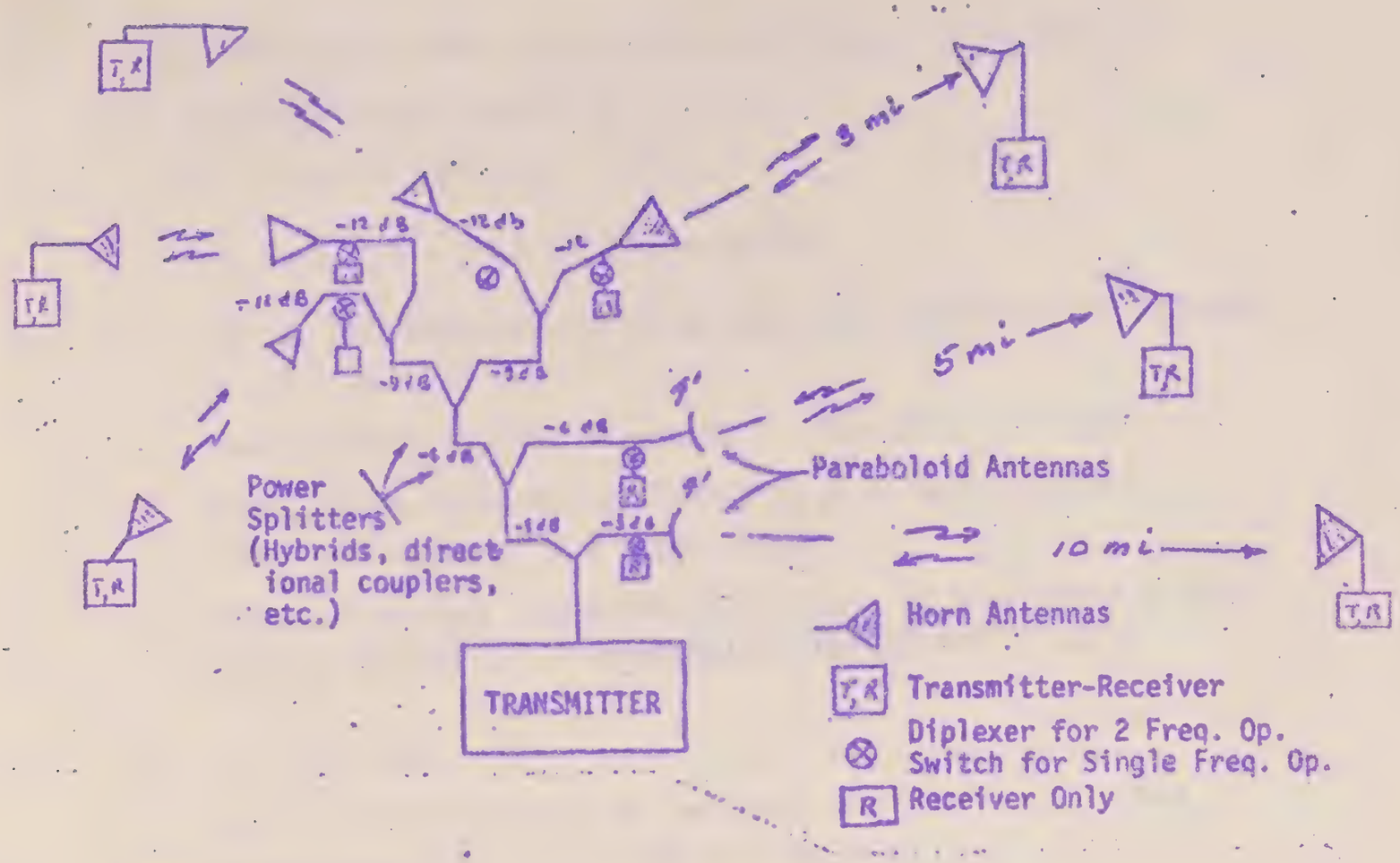
NOTE: The far field criteria commonly used for [illegible]
is range symmetrical surfaces is [illegible]
The distance in the above example is [illegible]
both criteria. (D = diameter of surface)

Example 3

The purpose of this example is to illustrate that an [illegible]
for each direction in a multidirection antenna [illegible]
transmission line a high data rate [illegible]
technique is most effective for one direction [illegible]
can easily be modified to this if separate [illegible]
[illegible] in a planning system layout all [illegible]
[illegible] on a common effective frequency pool. [illegible]
this uncertainty would be [illegible] sections for one [illegible]
a more realistic" of a number of distributed [illegible]

[illegible] signal [illegible]
[illegible] reference. Four stations [illegible]
[illegible] are located [illegible]
the signals provide some margin the [illegible] 20 db is [illegible]
[illegible] which each of the [illegible]
[illegible] of 99.9%. [illegible]
[illegible] larger than d' [illegible]
[illegible] of operation is [illegible]
[illegible] very high quantity. Due to [illegible]
[illegible] for error [illegible]
[illegible] used for this [illegible]
[illegible] as a real example. [illegible]
[illegible]

[illegible] used for [illegible]



5.9.2 Antennas

At 8 GHZ a 1 ft. aperture has a gain above isotropic of 29 db (see table I)

a. Four ft. paraboloid aperature efficiency of 0.55 is assumed.

Therefore:

$$\text{Gain} = 29 + 10 \log \left(\frac{\pi D^2}{4}\right) 0.55 = 29 + \log 0.55 (4\pi) = 29 + 8.9 = \boxed{37.4 \text{ db}}$$

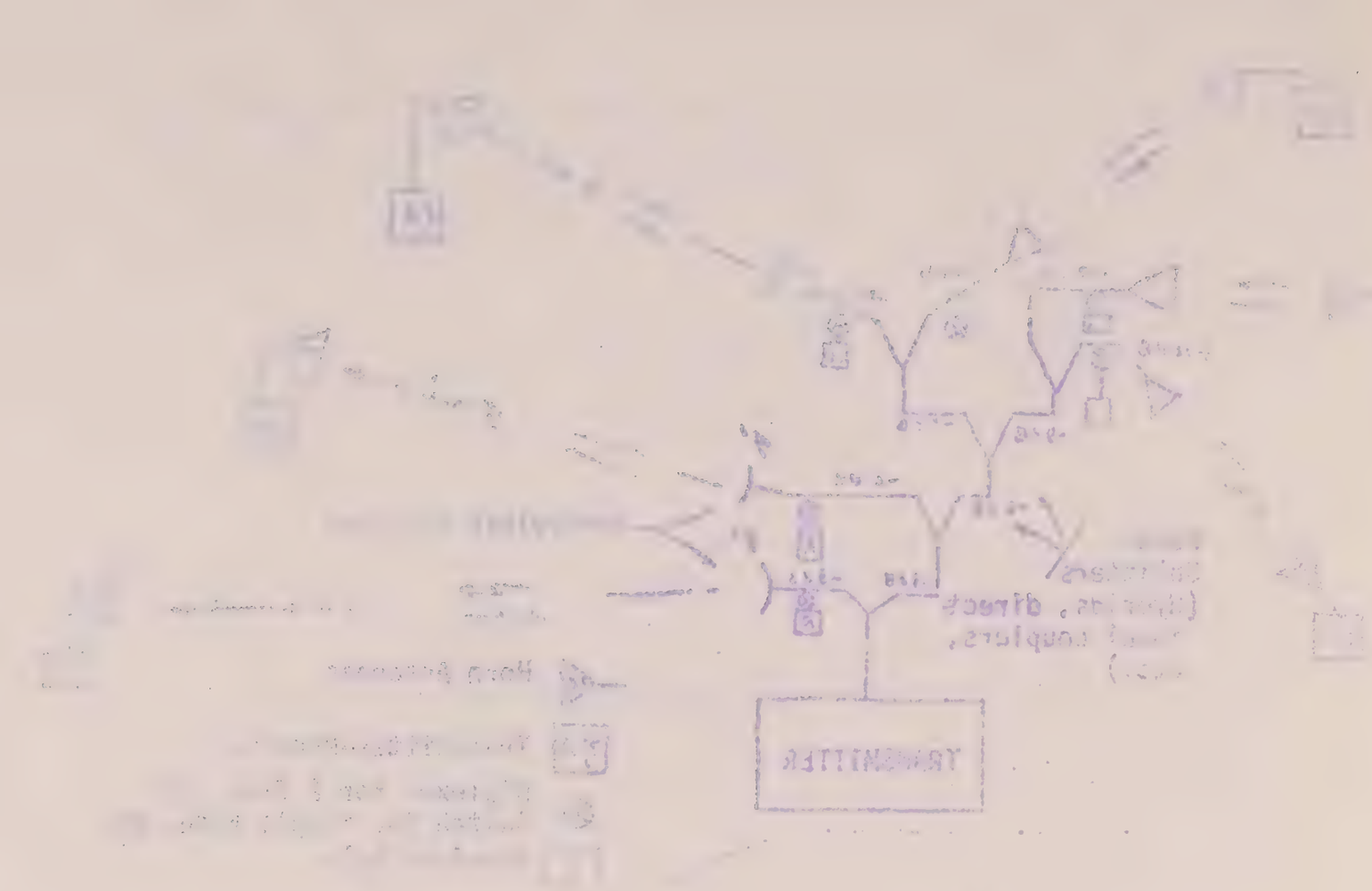
$$\text{Beamwidth} = \beta = \frac{70\lambda}{D} = \frac{70 \times 1.5}{48} \simeq \boxed{2.2 \text{ DEGREES}}$$

b. Horn - Assume aperture of about 1.8 sq. ft. (approx. 14"X18") and aperture efficiency of 0.45 (i.e. relatively short horn)

Therefore:

$$\text{Gain} = 29 + 10 \log (1.8 \times 0.45) = 29 + 10 \log 0.8 = 29 - 1 = \boxed{28 \text{ db}}$$

E Plane Beamwidth $= \beta = \frac{70\lambda}{a} \simeq \frac{70 \times 1.5}{18} \simeq$ 6 DEGREES


TRANSMITTER

5.9.3 Required Transmit Power and Resulting Fade Margins on Shorter Paths

a. Required transmit power, 10 mile path.

α = 36.6 + 78 + 20 = 134.6 db

Net path loss = 134.6 -37.8-28 = 69.2 db

For 100 KB/S data rate and 20 db fade margin required receive power is -95 + 20 = -75 dbm.

Power required at input to antenna = -75 + 69.2 =-5.8 dbm.

Since antenna is located at first 3 db power split required transmitter power = -5.8 + 3 = -2.8 dbm.

Therefore assume a transmitter power output of 1 milliwatt (0 dbm) allowing about 3 db for transmission line and filter losses.

b. Five Mile Path

The five mile path has 3 db less power and 6 db less path loss hence fade margin on this path will be 23 db.

c. Three Mile Paths

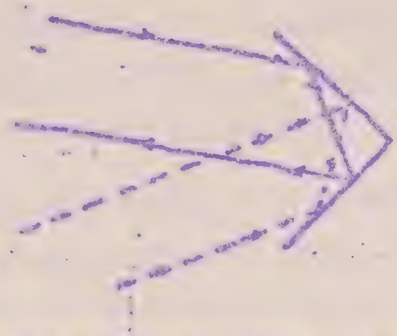
Horns with a gain of 28 db are used on both ends of the shorter paths. Further additional power splitter loss is seen in these paths. For 3 mile path space loss is 124 db and net space loss using 28 db horns is 68 db. The transmit power is attenuated 12 db by the power splitter hence receive power on these paths is -3-12-68 =-83 DBM. Fade margin is -83- (-95) = 12 db which should be quite adequate for most 3 mile paths.
NOTE: (3 db allowed for filter losses)

5.9.4 Increased Data Rate

If we wish to increase the data rate to 10 MB/S the transmit power must be increased by 20 db or to 100 milliwatts. This, from a hardware point of view, costs little more than the 1 milliwatt transmitter because of fixed costs in frequency control, modulation, etc. Therefore such a system can operate at a relatively high data rate with a modest transmitter power requirement and with reasonable size antennas.

5.10 Corner Reflectors

A 90 degree corner reflector has the interesting property of reflecting a signal back to its source



And for this reason is often used as radar markers. This leads to an interesting phenomenon which has been observed acoustically and is almost certain to occur with microwave radiation. A fairly common steel siding for industrial buildings, is formed as sketched below:

If one creates a sound impulse near such an structure a relatively strong echo (compared to a flat surface) is returned as a "chirp". It is concluded that this results from the corrugations acting as corner reflector. Since the wavelength of sound in air at 1 KHZ is about the same as the electrical wave length of a 1 GHZ microwave signal, it is expected that a very dispersive microwave echo would also be quite noticeable. However, even if the structure is 2000 ft. long the dispersion is small compared to that from multiple more distant objects such as shown in example 6 above.

5.11 Comments and Cautions

For the above examples the power required for line of sight communication varied by factors as large as 4×10^7 (76 db) for a constant path length of 5 miles. The largest power difference seen in these examples was at 8 GHZ between the omni and directional antenna (4' paraboloids) (examples 3 & 4). The following conclusions can be drawn from these examples:

a. If omni antennas are to be used the optimum frequency to use is the lowest available within the constraints of practical antenna size (i.e. should not exceed 5 or 6 ft. for hand held terminal).

(This conclusion is reached without even considering propagation but the better propagation characteristics of longer wavelengths through obstructed paths further support this conclusion).

b. If directional antennas are used the higher frequencies are to be favored, until rain attenuation becomes a factor (i.e. above 10 GHZ, see Section 6), because of the increasing gain with frequency of a constant size aperture. Note that in comparing the net path loss between isotropic antenna and antennas with constant aperture the ratio of net path loss for the two configurations is proportional to F^4.

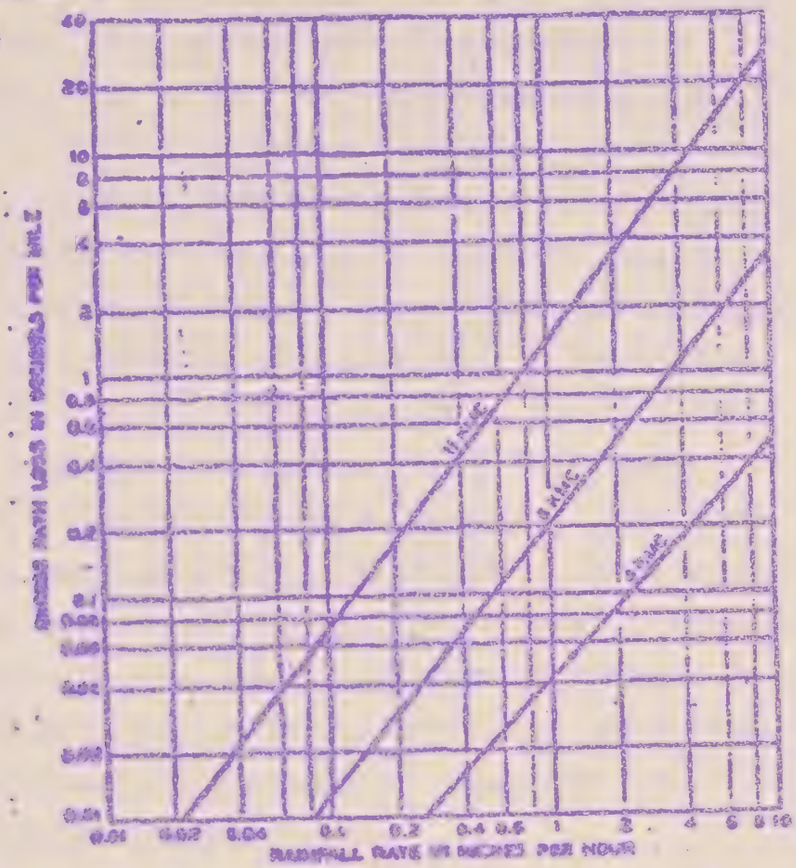
c. Even with moderate size directional antennas (i.e. 1 or 2 sq. ft. apertures) high data capacities are possible with quite low transmit powers.
(Nothing has been said here about the coherency of the channel but experience with wideband microwave systems with directive antennas indicate coherency adequate for data rates of at least tens of megabits even under multipath propagation conditions if adequate fade margin is provided.

d. Large Reflecting Structures Will Present a Substantial Echo Problem for Omni Systems

A word of caution is offered relative to transmit powers calculated. No allowance was made for obstruction loss or signal cancelation due to multipath in the examples above though the 20 db C/N is 5 to 7 db higher than required for low error rates (i.e. lower than 10^{-7}) in absence of interference. Therefore, these examples are valid only for good lines of sight paths. Measurements by Young[2] for a mobile radio environment indicates median signal values, at a range of 2 miles and a relatively low VHF frequency of 150 MHZ, was about 27 db below that calculated for line of sight transmission.

6.0 Rain Attenuation

Attenuation due to rainfall is a function of rainfall rate, frequency and raindrop size. This subject has been investigated by numerous workers in this field and adequate data exists relative to attenuation characteristics and statistics of rainfall to allow reliable system design well into the millimeter region. Therefore this subject is discussed only briefly in these notes. Available data indicates that rain attenuation is seldom a significant factor affecting radio system design below frequencies of about 10 GHZ. A curve of attenuation per mile as a function of frequency and rainfall rate from Hathaway and Evans[3] is included below.



Rain Attenuation VS. Rainfall Rate

The frequency band from 13 to 16 GHZ might be used for high data rate paths with directive antennas. Since high gain can be obtained from moderate size antennas adequate signal margin for rain can be easily provided even in this band if path lengths aren't excessive (i.e. less than 10 miles or so). Even the millimeter region (36 GHZ and higher) is now frequently considered for similar applications where repeater spacing of a few miles is practical.

7.0 Coherency of Line-of-Sight Paths

Since it has been mentioned above that use of directive antennas offer capability of high data rates with low transmit power this statement should be justified on the basis of coherency bandwidth. This subject like rain attenuation is not discussed in any detail in these notes but adequate data exists in current literature to support this opinion. In many high data rate systems it is the bandpass distortion under multipath fading conditions that control error rate (because of intersymbol interference) and not the decrease in signal strength. However even under multipath fading conditions the signal dispersions that cause fading are small (i.e. a few nanoseconds). This may be shown thru geometrical considerations and has been proven by several investigators using sweep frequency techniques. Bandpass distortion over a 20 MHZ band under multipath fading conditions has been studied by Kaylor[4], and statistical distribution of bandpass distortion as a function of level of fade derived from this reference is shown as Figure 7-1. Collins has performed lab measurements of error rate performance of a 21.5 MB/S 4Ø PSK system under simulated multipath conditions using a two ray model in which both multipath delay and level of resulting fade were varied. Tests have also been performed at 11 GHZ in the Washington area over a 25 mile path using Collins mw-609 microwave requirement (5 watt output). Since this path was designed for 35 to 40 db fade margin, good error rate performance was obtained at 21.5 MB/S data rate even under conditions of moderate to heavy rainfall. Test path was chosen relatively long, for a 11 GHZ path, in order to confirm predicted error rate performance under multipath fading and high rain attenuation conditions.

Tests have been reported by Babler[5] of Bell Telephone labs in which a bandwidth of about 34 MHZ at 6 GHZ was continuously sampled in frequency increments of 550 KHZ. Results shown are "worst case" for a fading channel and indicate that for a narrow band channel the signal attenuation is likely of more importance than the phase shift. Of particular interest here is that the deep fade can be modeled by a weak long delayed echo added to a channel already faded by a stronger echo of much shorter delay. (long, as used here is only a few nano seconds). This agrees with tests reported by Kaylor[4].)

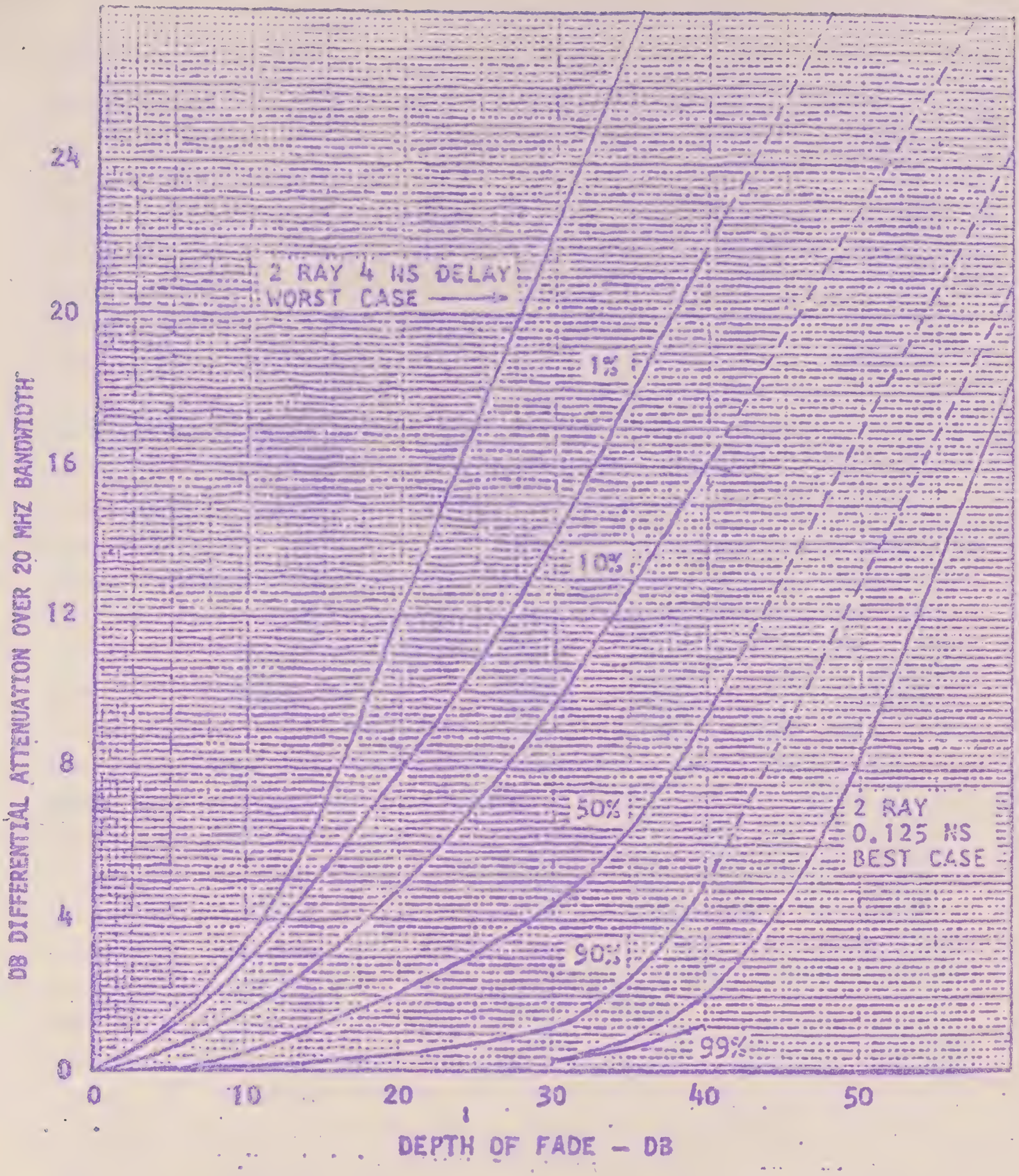


FIGURE 7-1 PERCENT OF TIME THAT ATTENUATION SLOPE EXCEEDS VALUE ON ORDINATE VS. FADE BELOW FREE SPACE ATTENUATION ON ABCISSA. FROM DATA BY KAYLOR[4] AT A FREQUENCY NEAR 4 GHZ. SLOPE MEASURED OVER A 20 MHZ BANDWIDTH.

Conclusions

Space loss increases with increasing frequency only because space loss has been defined as the loss between isotropic antennas and hence in our model the capture area of the receiving antenna decreases as the inverse square of frequency. If we choose as a system model antennas of constant aperture the capture area of the receive antenna remains constant and the transmit antenna directivity increases with increasing frequency. Hence, the relationship of the isotropic antenna model and the constant aperture model varies as the 4th power of frequency.

For the constant aperture model beamwidth decreases with frequency and this can be a disadvantage if we wish to transmit and/or receive to and from a number of locations. However, if the objective is to build directive networks this feature favors the higher frequencies since this feature provides higher isolation between stations and hence allows a higher density of stations and therefore a higher transmission capacity over a given area.

A particularly impressive characteristic of the higher microwave frequencies is that the required transmit power can be quite low for moderate size apertures and path lengths of a few miles even for data rates of a few MB/S. This leads to a concept of directive networks using low cost transceivers and a moderate amount of alternate routing . In such a network we can be a little extravagant with data rate since it costs very little. In such an arrangement any redundancy should be put in alternate routing rather than in an equipment along any one route in order to keep equipment cost low. What is envisioned here is a microwave freouency directive network which performs the routing, trunking, switching and record keeping functions. Messages may either originate at repeater and station locations, or may enter the network from mobile terminals which operate in VHF or UHF frequency range using omni antennas. Though this system model requires operation in two widely separated frequency bands it appears to have sufficient potential for large traffic capacity to justify further investigation.

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